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Novel fabrication technique for high-performance diamond nanophotonic structures

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Freestanding diamond nanostructures are etched from a bulk diamond substrate and integrated with evanescently coupled superconducting nanowire single-photon detectors.

Diamond nanophotonics is a rapidly evolving platform in which non-classical light—emitted by defect centers in diamond—can be generated, manipulated, and detected in a single monolithic device (e.g., for quantum information processing applications).[1–3] For instance, it is possible to engineer many different nanostructures in which some of diamond's extraordinary material properties (e.g., high refractive index, wide band gap, and large optical transmission range) are exploited.[4,5] The relatively large Kerr non-linearity[6] of diamond also makes it an attractive platform for on-chip nonlinear optics at visible and IR wavelengths.[7] For example, this nonlinearity could be used to convert the frequency of photons generated by color centers in diamond (i.e., from their typical visible wavelengths to telecom wavelengths).[8] In turn, this would enable transmission of quantum information and distribution of quantum entanglement[9,10] over long distances. Such integrated diamond–quantum photonics platforms, however, require the use (and realization) of high-performance single-photon detectors that have broadband photon sensitivity (and are integrated on the same diamond chip).

Superconducting nanowire single-photon detectors (SNSPDs) are a class of cutting-edge photon detectors that have been shown to outperform other technologies in terms of detection efficiency, dark counts, timing jitter, and maximum count rates.[11–13] SNSPDs typically consist of narrow nanowires that are patterned into an ultrathin (4–8nm) superconducting film (e.g., of niobium nitride).[14] In addition, the current of the nanowires is biased close to the critical current of the superconductor material so that when an incident photon is absorbed by the wire, a small resistive hotspot forms and generates a voltage pulse (which is then amplified and measured).[15] The performance of SNSPDs is critically dependent on nanowire structural uniformity. It is therefore crucial to deposit the nanowires on smooth substrate surfaces, i.e., to avoid constrictions that would have a detrimental effect on detection efficiency.[16]

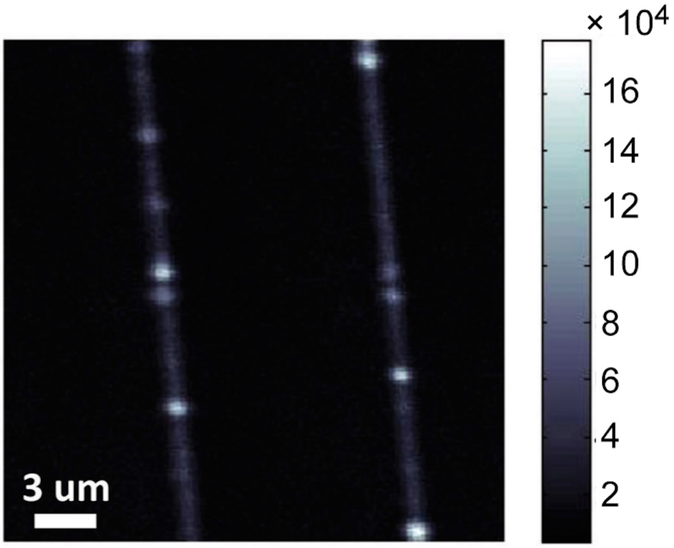

Figure 1. *Confocal scan of a suspended diamond waveguide, where bright spots indicate locations of implanted single nitrogen vacancy centers.*

In our work,[17,18] we have therefore developed a novel fabrication procedure with which we can etch freestanding diamond nanostructures directly from a bulk substrate. We use these freestanding diamond waveguides to guide the emission from diamond color centers—nitrogen[19] or silicon vacancies (NVs or SiVs) (see Figure 1) that we implant within the

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nanostructures—to evanescently coupled niobium titanium nitride (NbTiN) SNSPDs. Specifically, our goal is to couple the emission of the quantum emitters (i.e., the implanted NV/SiV centers) to the fundamental mode of the diamond waveguide. The evanescently coupled SNSPDs can thus be used to detect the color centers, whilst the pump laser that scatters into the waveguide is filtered out.

A scanning electron microscope image of several of our suspended (freestanding) diamond waveguides (with triangular cross sections) is shown in Figure 2(a). We etched these waveguides from single-crystal diamond with the use of our specific angled-etching fabrication method. The waveguides are also supported periodically by thin pieces of diamond. We create these supports by slightly increasing the width of the waveguide at the support locations. This allows long segments of the waveguide to remain freestanding (while not perturbing the waveguide node).[20] In addition, single SNSPD curves—see Figure 2(b)—are located on either end of the waveguides. The SNSPDs are then connected to titanium or gold contact pads for electrical readout purposes.

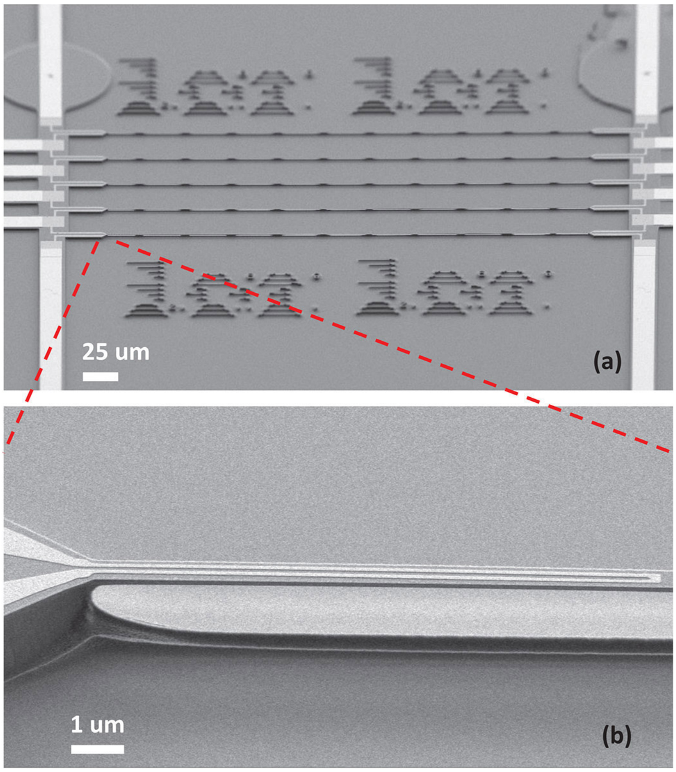

Figure 2. *Scanning electron microscope images showing (a) several freestanding diamond waveguides (with triangular cross sections) that have two superconducting nanowire single-photon detectors (SNSPDs) at either end (and that are connected to titanium or gold pads) and (b) a SNSPD patterned directly on top of the suspended diamond waveguide.*

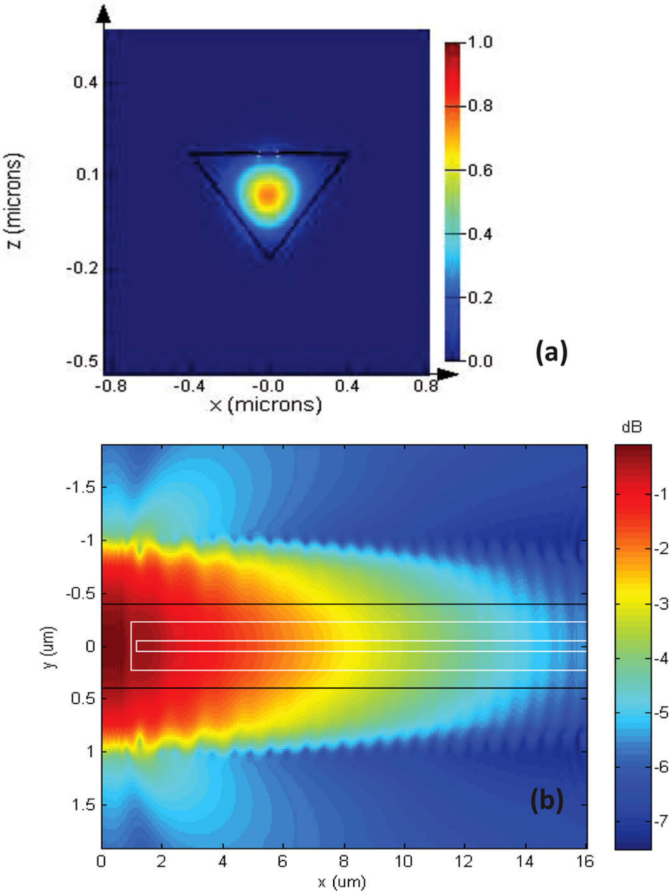

Figure 3. *Finite-difference time-domain simulations of a diamond waveguide SNSPD. (a) Normalized field distribution of the optical mode in the waveguide. (b) Absorption characteristics of the device (propagation intensity shown on a logarithmic scale) along the propagation direction. White lines indicate the location of the 10.5nm-thick niobium titanium nitride superconducting nanowire.*

Finite-difference time-domain simulations of our diamond waveguide SNSPD device are shown in Figure 3. The normalized field distribution of the optical mode in the diamond waveguide is shown in Figure 3(a). In addition, the absorption characteristics of the device—Figure 3(b)—indicate that more than 99% of the optical power has been absorbed by the SNSPD after a propagation distance of 15μm.

The photon-counting performance of an SNSPD on one of our suspended diamond waveguides (at 4.2K), when illumi-

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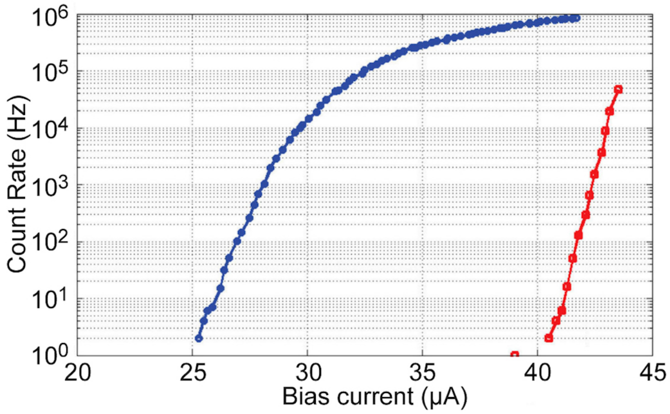

Figure 4. *Photon-counting performance of an SNSPD (at 4.2K) on a suspended diamond waveguide that is illuminated by 705nm photons. The intrinsic dark count rate and a representative count rate are shown by the red and blue curves, respectively.*

nated with vertically incident 705nm photons, is depicted in Figure 4(a).

In summary, we have developed a platform with which SNSPDs can be fabricated on freestanding waveguides that are etched from single-crystal diamond (which can host quantum emitters with good spectral properties).[21] We have also characterized the photon-counting performance of our fabricated detectors. With our approach it is possible to achieve monolithic and scalable integration of diamond quantum optical circuits that are based on defect color centers. In the next stages of our work, we plan to improve the filtering of the pump beam (i.e., that is used to excite the color centers) so that the SNSPDs are no longer saturated by pump photons.

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References

1. I. Aharonovich, A. D. Greentree, and S. Prawer, *Diamond photonics*, **Nat. Photon. 5**, pp. 397–405, 2011.
2. B. J. M. Hausmann, J. T. Choy, T. M. Babinec, B. J. Shields, I. Bulu, M. D. Lukin, and M. Lončar, *Diamond nanophotonics and applications in quantum science and technology*, **Phys. Status Solidi A 209**, pp. 1619–1630, 2012.
3. M. Lončar and A. Faraon, *Quantum photonic networks in diamond*, **MRS Bull. 38**, pp. 144–148, 2013.
4. M. J. Burek, N. P. de Leon, B. J. Shields, B. J. M. Hausmann, Y. Chu, Q. Quan, A. S. Zibrov, H. Park, M. D. Lukin, and M. Lončar, *Free-standing mechanical and photonic nanostructures in single-crystal diamond*, **Nano Lett. 12**, pp. 6084–6089, 2012.
5. B. Khanaliloo, M. Mitchell, A. C. Hryciw, and P. E. Barclay, *High-Q/V monolithic diamond microdisks fabricated with quasi-isotropic etching*, **Nano Lett. 15**, pp. 5131–5136, 2015.
6. R. W. Boyd, **Nonlinear Optics**, Academic Press, 2008.
7. B. J. M. Hausmann, I. Bulu, V. Venkataraman, P. Deotare, and M. Loncar, *An on-chip diamond optical parametric oscillator*, **arXiv:Optics 1309.1178**, 2013.
8. M. G. Raymer and K. Srinivasan, *Manipulating the color and shape of single photons*, **Phys. Today 65** (11), p. 32, 2012.
9. E. Togan, Y. Chu, A. S. Trifonov, L. Jiang, J. Maze, L. Childress, M. V. G. Dutt, *et al.*, *Quantum entanglement between an optical photon and a solid-state spin qubit*, **Nature 466**, pp. 730–734, 2010.
10. H. Bernien, B. Hensen, W. Pfaff, G. Koolstra, M. S. Block, L. Robledo, T. H. Taminiau, *et al.*, *Heralded entanglement between solid-state qubits separated by three metres*, **Nature 497**, pp. 86–90, 2013.
11. F. Marsili, V. B. Verma, J. A. Stern, S. Harrington, A. E. Lita, T. Gerrits, I. Vayshenker, *et al.*, *Detecting single infrared photons with 93% system efficiency*, **Nat. Photon. 7**, pp. 210–214, 2013.
12. R. H. Hadfield, *Single-photon detectors for optical quantum information applications*, **Nat. Photon. 3**, pp. 696–705, 2009.
13. M. K. Akhlaghi, H. A. Atikian, A. Eftekharian, M. Lončar, and A. H. Majedi, *Reduced dark counts in optimized geometries for superconducting nanowire single photon detectors*, **Opt. Express 20**, pp. 23610–23616, 2012.
14. S. N. Dorenbos, E. M. Reiger, U. Perinetti, V. Zwiller, T. Zijlstra, and T. M. Klapwijk, *Low noise superconducting single photon detectors on silicon*, **Appl. Phys. Lett. 93**, p. 131101, 2008.
15. G. N. Gol'tsman, O. Okunev, G. Chulkova, A. Lipatov, A. Semenov, K. Smirnov, B. Voronov, A. Dzardanov, C. Williams, and R. Sobolewski, *Picosecond superconducting single-photon optical detector*, **Appl. Phys. Lett. 79**, pp. 705–707, 2001.
16. A. J. Kerman, E. A. Dauler, J. K. W. Yang, K. M. Rosfjord, V. Anant, K. K. Berggren, G. N. Gol'tsman, and B. M. Voronov, *Constriction-limited detection efficiency of superconducting nanowire single-photon detectors*, **Appl. Phys. Lett. 90**, p. 101110, 2007.
17. H. A. Atikian, A. Eftekharian, A. J. Salim, M. J. Burek, J. T. Choy, A. H. Majedi, and M. Lončar, *Supercondcuting nanowire single photon detector on diamond*, **Appl. Phys. Lett. 104**, p. 122602, 2014.
18. H. Atikian, s. Meesala, A. Sipahigil, R. Evans, D. Sukachev, J. Pacheco, E. Bielejec, *et al.*, *Diamond nanophotonics structures integrated with superconducting nanowire single photon detectors*, **Proc. SPIE 9858**, pp. 9858–15, 2016.
19. Y. Chu, N. P. de Leon, B. J. Shields, B. Hausmann, R. Evans, E. Togan, M. J. Burek, *et al.*, *Coherent optical transitions in implanted nitrogen vacancy centers*, **Nano Lett. 14**, pp. 1982–1986, 2014.

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20. M. J. Burek, Y. Chu, M. S. Liddy, P. Patel, J. Rochman, S. Meesala, W. Hong, Q. Quan, M. D. Lukin, and M. Lončar, *High quality-factor optical nanocavities in bulk single-crystal diamond*, **Nat. Commun. 5**, p. 5718, 2014.
21. R. E. Evans, A. Sipahigil, D. D. Sukachev, A. S. Zibrov, and M. D. Lukin, *Narrow-linewidth homogeneous optical emitters in diamond nanostructures via silicon ion implantation*, **Phys. Rev. Appl. 5**, p. 044010, 2016.